Photonic crystal microcavities for strong coupling between an atom and the cavity field

Jelena Vučković, Marko Lončar
Electrical Engineering Department, CalTech 136-93, Pasadena, CA 91125, U.S.A.
phone: (626) 395-2207, fax: (626) 683-9547, e-mail: jela@caltech.edu

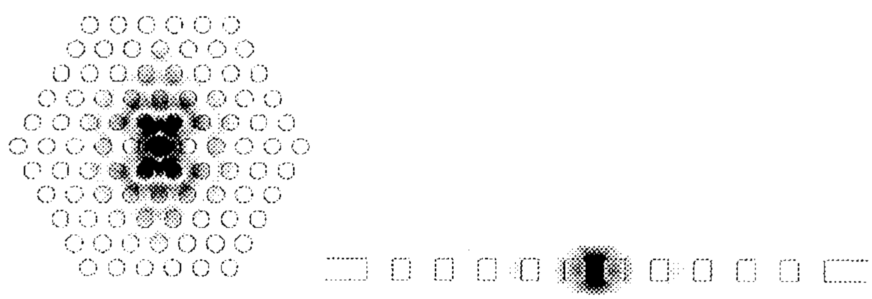
Hideo Mabuchi
Physics Department, CalTech 12-33, Pasadena, CA 91125, U.S.A.

Axel Scherer
Electrical Engineering Department, CalTech 110-36, Pasadena, CA 91125, U.S.A.

Various passive and active optical devices can be constructed by introducing point or line defects into a periodic array of holes perforating an optically thin semiconductor slab. This technique was employed in making a semiconductor (InGaAsP) laser[1] (emitting at $\lambda = 1.55 \mu m$) with a mode volume as small as $0.03 \mu m^3$, and for demonstrating Si optical waveguides with sharp bends.[2] In these structures, light is confined laterally by means of distributed Bragg reflection and vertically by total internal reflection. The advantage of this approach should lie in facilitating the integration of many optical components on a single chip.

Microcavity formation via alteration of the refractive index of a single defect hole in a hexagonal photonic crystal (PC) has been previously analyzed theoretically.[3] In that analysis, the radius of the defect was equal to that of the unperturbed PC holes, but its refractive index was tuned between one and the refractive index of the slab. It was shown that, in the described structure, dipole defect modes can be excited with quality factors as high as 20000 and with mode volumes in the range of several half-cubic wavelengths (as measured inside the dielectric material).

In the current work we consider the design of PC microcavities to achieve strong coupling between



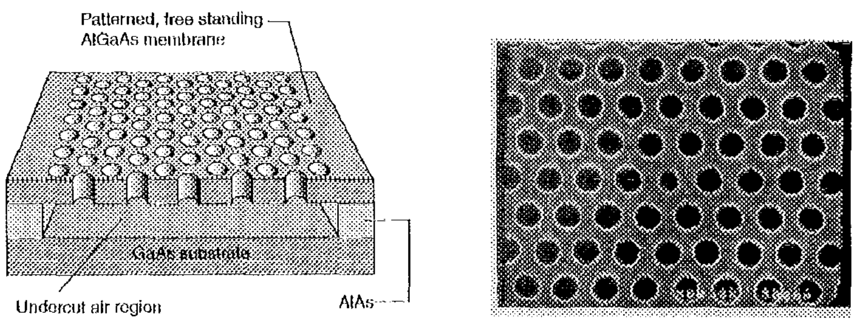
(a) (b)

Figure 1: E-field intensity plots of the dipole mode in the cavity formed by reducing a radius of a single PC hole.

the cavity field and a single 'gas-phase' atom (that is, an atom located in free space rather than contained as an impurity in the dielectric slab). Our long-term goal is to investigate photonic bandgap structures for single-atom cavity quantum electrodynamics in the strong coupling regime.[4] For this purpose, the microcavity mode quality factor (Q) has to be as large as possible and the mode volume (V_{mode}) as small as possible. These two design rules are also followed when designing PC microcavities for semiconductor lasers. However, in a cavity for strong coupling, an atom must be trapped at the point where it interacts most strongly with the cavity field. Therefore, an additional design goal is imposed in this case: the cavity mode should have the highest E-field intensity in the air region. When designing a laser cavity, the problem is opposite: one tends to maximize the overlap between the gain region and the cavity field and, therefore, wants to have the strongest E-field in the semiconductor region.

We have analyzed theoretically (using the 3-d finite-difference time-domain method) some mode properties of cavities produced by reducing a radius of a single hole in hexagonal PC perforating an optically thin semiconductor slab. The material and PC properties were chosen in such a way that cavities operate at $\lambda = 852nm$, the wavelength corresponding to the atomic transition in ^{133}Cs. The obtained electric field distribution of the dipole defect mode is shown in Figure 1. An atom should be trapped at the center of the defect hole, where it couples most strongly with the cavity field. By tuning the radius of the defect hole, as well as PC and slab parameters, we were able to obtain $V_{mode} = 0.18(\frac{\lambda}{2})^3$ with $Q = 32000$ for the dipole defect mode. For this particular design, the defect hole had a diameter of about $100nm$. The estimated critical atom and photon numbers[4] were $N_0 = 1.8 \cdot 10^{-3}$ and $m_0 = 10^{-7}$, respectively. Therefore, it should be possible to achieve very strong coupling between atoms and PC cavities, even with this simplest cavity design. Critical issues for further investigation include efficient coupling of light in and out of the PC microcavity, as well as the significance of surface effects that could perturb atomic radiative structure within the small defect hole. The extremely small mode volume in these structures also poses an interesting theoretical question of how standard cavity QED models must be modified when the single-photon Rabi frequency greatly exceeds the atomic hyperfine spacings.

We have also developed the fabrication procedure for making these cavities in AlGaAs. The cross



(a) (b)

Figure 2: (a) Cross section of the structure and (b) SEM picture showing the top view of the fabricated structure.

section of the structure and the SEM picture showing the top view of the fabricated cavity are shown in Figure 2.

In conclusion, we have demonstrated theoretically that PC cavities can be designed for strong interaction with atoms trapped in one of PC holes. At present, we are working on further optimization of the design and the characterization of fabricated structures.

References

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